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EXPERIMENTAL INVESTIGATION ON HARDNESS, MICROSTRUCTURE AND SURFACE ROUGHNESS OF MARAGING STEEL PARTS PRODUCED BY DIRECT METAL LASER SINTERING TECHNIQUE

D. APPARAO[1] & M. V. JAGANNADHA RAJU[2]

[1]*Assistant Professor, Department of Mechanical Engineering, Aditya Institute of Technology and Management, Tekkali, Andhra Pradesh, India*

[2]*Assistant Professor, Department of Mechanical Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, India*

ABSTRACT

Direct metal laser sintering (DMLS) is an additive manufacturing technique used to fabricate metal parts directly from the computer- aided design (CAD) data without any further machining operations. The DMLS technique is used in various applications in aerospace, automotive, medical and tooling industries. In this view, this paper presents an investigation of the hardness, surface roughness and microstructure of maraging steel parts produced by DMLS technique. The input process parameters, i.e. laser power, scan speed and hatching space were selected and conducted experimentation based on Taguchi design. The hardness, microstructure and surface roughness of the parts were analyzed before and after heat treatment and sandblasting.

KEYWORDS: Additive Manufacturing (AM), Direct Metal Laser Sintering (DMLS), Maraging Steel, Taguchi Method, Hardness, Microstructure & Surface Roughness

Original Article

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INTRODUCTION

Additive Manufacturing (AM) is a great technique to manufacture the intricate parts in the fields of medical, aerospace and automotive applications with high flexibility to meet desired mechanical properties and model as CAD model [1]. Direct Metal Laser Sintering (DMLS) is one type of AM technique to fabricate those products from the metal powder such as Aluminium [2]. Maraging steels are well known for their high strength, high fracture toughness, good weldability and dimensional stability during aging. Due to this unique combination of several attractive features, maraging steels find extensive use in high performance industrial and engineering parts such as aerospace and motor racing applications. Some of the applications can be listed as rocket motor castings, drill chucks, tools for punching, extrusion, plastic injection molds and metal casting dies [3]. Maraging steels offer an attractive alternative to the medium to high carbon tool steels since they do not suffer any problems like high carbon content promoting the corrosion and quench cracking which may only become evident during service and result in unexpected failure. The low carbon content of maraging steels reduces the risk for quench cracking, while the high nickel content and absence of carbides provides a good corrosion resistance [4]. The energy density (ED) is a key factor depending upon machining process parameters such as laser power, scan speed, hatching space and powder layer thickness, in fabricating a part with desired properties by DMLS technique [5]. It is possible to change the density and amount of the pores inside the DMLS product by changing

the Energy density as well as changing those four machining process parameters, which can directly reflect the mechanical properties of the product [6, 7]. As the melting property of the powder is also influencing on those factors, so those surface properties are also depending on machining process parameters [8].

DMLS is a promising technology due to almost unlimited geometrical freedom, especially for tooling applications. It is possible to produce complex geometries with internal cavities by the DMLS such as conformal cooling channels. A conformal cooling channels are generally considered to be almost impossible to be built by conventional machining techniques, but allow a major reduction in injection molding cycle time. Therefore, DMLS of maraging steels can offer new opportunities in tooling applications by producing parts with almost full density and high freedom in geometrical complexity. In this study, DMLS of maraging steel MS1grade is taken under investigation regarding many aspects. In this study, the change of hardness, microstructure and surface quality was determined while varying the process parameters, i.e., Laser power, scan speed, Hatch spacing, from the recommended range of values by the DMLS machine vendor.

EXPERIMENTAL DETAILS

Maraging steel is in powder form was chosen as sintering material and its chemical composition is shown in Table 1. The scanning electron micrograph (SEM) of maraging steel powder particles used in this study is shown in figure 1. It can be seen from the figure that the powder particles are spherical in shape and size of the particles variying between 3–60 μm. The mild steel rectangular bar is used as the substrate material to sinter the maraging steel powder on it.

Table 1: Chemical Composition of Maraging Steel

Elements	Ni	Co	Mo	Ti	Al	C	Cr, Cu	Si, Mn	S,P	Fe
Weight %	17-19	8.5-9.5	4.5-5.2	0.6-0.8	0.05-0.15	<0.03	<0.5	<0.1	<0.01	Bal.

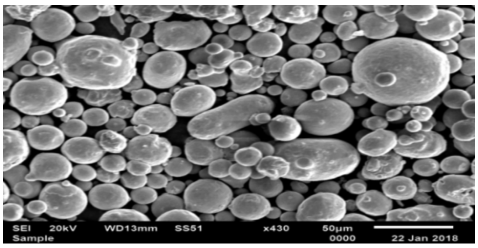


Figure 1: SEM of Maraging Steel Powder

The Direct Metal Laser Sintering machine was used to manufacture all test specimens in the nitrogen purging atmosphere as shown in figure 2. The protective gas allows maintaining the oxygen content to low levels for preventing the oxidation of maraging steel powders during part fabrication. The machine is equipped with a 400 W fiber laser with 80 μm laser beam spot and has a build chamber of size 250 × 250 × 250 mm. The platform building was maintained at 40°c to avoid the build samples from warping due to non-uniform thermal expansion at elevated temperatures. The layer thickness of the powder is maintained constant at 40μm by lowering the build platform. A mild steel platform is placed on the building platform (XY table) and leveled.

Figure 2: DMLS Machine (Model – EOSINT M280/400 W)

Figure 3: As-fabricated Specimens

In order to manufacture all test specimens with best physical and mechanical properties, the experiments were conducted using the Taguchi method. Taguchi method has been applied in determining the best possible combination of process parameters to produce desired output. In the present work laser power, laser scan speed and hatch spacing have been used as input, process parameters for achieving maximum hardness as the desired output. The input process parameters for direct metal laser sintering and their levels are shown in Table 2.

Table 2: Input Process Parameters and Their Levels

S.No.	Parameter	Level1	Level2	Level3	Level4	Level5
1	Laser power (W)	230	260	290	320	350
2	Scanning speed (mm/sec)	750	850	950	1050	1100
3	Hatch spacing (mm)	0.10	0.11	0.12	0.13	0.14

RESULTS AND DISCUSSIONS

The experimental plan based on the L25 orthogonal array as shown in Table 3. The energy density is one of the key factors depending upon machining process parameters such as laser power (P), scan speed (v), hatching space (h) and powder layer thickness (t), in fabricating a part with desired properties by DMLS technique. The Energy density is calculated by the equation $ED = P/(v \times h \times t)$ J/mm³. The hardness and surface roughness of the specimens were determined by using a Rockwell hardness tester and surface roughness tester respectively. The specimens of size 10 mm X 10 mm X 10 mm in cubic shape were fabricated with 0° orientation as shown in figure 3 by varying the process parameters to study the effect of process parameters on the hardness, microstructure, and surface roughness. At a higher energy density, i.e. 102.94 J/mm³, the powder was highly melted and protrusions have grown and the recoater blade was struck and hence the specimen was not fabricated. The fabrication of specimen with high energy density, i.e. 102.94 J/mm³ was possible with 45° orientation.

Table 3: Experimental Plan Based on L25 Orthogonal Array

Exp. No.	Laser Power (W)	Scanning Speed (mm/sec)	Hatch Spacing (mm)	Layer Thickness (µm)	Energy Density (J/mm³)	Hardness (HRC)	Surface Roughness (µm)
1	230	750	0.1	40	76.66	36.76	4.56
2	230	850	0.11	40	61.49	36.38	3.36
3	230	950	0.12	40	50.43	32.68	3.12
4	230	1050	0.13	40	42.12	31.65	3.77
5	230	1100	0.14	40	37.33	28.63	6.09
6	260	750	0.11	40	78.78	33.91	4.37
7	260	850	0.12	40	63.72	37.83	1.83
8	260	950	0.13	40	52.63	34.16	3.16
9	260	1050	0.14	40	44.21	33.00	4.75

Table 3: Contd.,

10	260	1100	0.1	40	59.09	35.28	5.00
11	290	750	0.12	40	80.55	37.21	3.94
12	290	850	0.13	40	65.61	33.46	5.16
13	290	950	0.14	40	54.51	34.16	5.15
14	290	1050	0.1	40	69.04	35.83	5.51
15	290	1100	0.11	40	59.91	34.83	7.31
16	320	750	0.13	40	82.05	35.30	5.55
17	320	850	0.14	40	67.22	34.43	5.60
18	320	950	0.1	40	84.21	33.50	4.7
19	320	1050	0.11	40	69.26	32.40	5.48
20	320	1100	0.12	40	60.60	33.91	4.95
21	350	750	0.14	40	83.33	34.03	4.04
22	350	850	0.1	40	102.94	XX	XX
23	350	950	0.11	40	83.73	33.58	7.46
24	350	1050	0.12	40	69.44	34.50	4.94
25	350	1100	0.13	40	61.18	32.43	4.40

HARDNESS

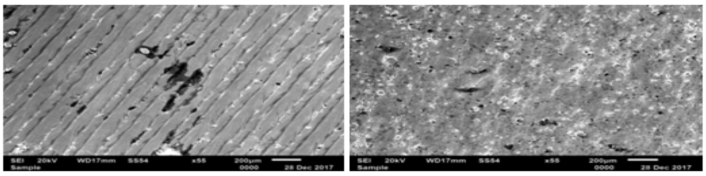
Hardness is one of the mechanical properties of metal which has the ability to resist deformation. In addition, the hardness is the resistance to scratching, cutting or abrasion. The higher the metal hardness will cause the higher resistance need to deform. The hardness of all the specimens was measured with the Rockwell Hardness tester according to the 150 kg loaded Rockwell C scale. Indentations were made at six different locations on the specimen, using a load of 150 kg. An average of all six readings was taken as the hardness of each specimen. The minimum and maximum hardness of the specimens is found to be 28.63 HRC and 37.83 HRC for the samples 5 and 7 respectively as shown in Table 3. Low hardness can be observed in energy density 37.33 J/mm³ and high hardness can be observed an 63.72 J/mm³. The higher hardness of the samples may be attributed to fine grain size and minimum porosity. Smaller the grain size more will be the obstacles for dislocation motion, thereby enhancing the resistance to plastic deformation resulting in higher hardness.

The hardness of the samples can be increased by the heat treatment operation. The superior properties of the maraging steels, i.e. good strength and toughness are achieved by the age hardening of a ductile, low-carbon bodycentered cubic (BCC) martensite structure with relatively good strength. Therefore, the aging heat treatment is standard for maraging steels. It is aimed to form a uniform distribution of fine Ni, Co, and Mo rich intermetallic precipitates during the aging of the martensite. These precipitates serve to strengthen the martensitic matrix. For maraging steel, the values recommended by the ASM Handbook are 3 to 8 hours at a temperature between 460°C and 510°C [9]. In this study, the duration of 6 hours at a temperature of 490°C was tested. The electric heated solutionizing furnace was used for the heat treatment process. After this heat treatment, a hardness of 55.33 HRC is achieved for the specimen 7, which means an increase of nearly 18 HRC compared to the as fabricated specimen.

MICROSTRUCTURE

The microstructure of Maraging steel specimens as fabricated at different energy densities are shown in Fig 4. Microstructure studies are carried out on top and side surfaces of the sample by using JEOL JSM 6610LV Scanning Electron Microscope. It is observed that the surface of the laser melted maraging steel without heat treatment and the laser path is clearly shown in Fig 4. Due to the surface tension effect, the formation of metallic balls occurred during the laser melting process and it leads to the poor surface finish. An increase in laser density resulted in merging of scan tracks and

overall smoothing of surfaces. Increasing laser energy density establishes a relatively high temperature that eases liquid flow to fill pores. This is due to the relatively low viscosity of melt and part density and hardness increases. The porosity can be observed in the microstructure at the energy densities 37.33 J/mm³and 61.18 J/mm³. Less porosity can be observed in the energy density 63.72 J/mm³.



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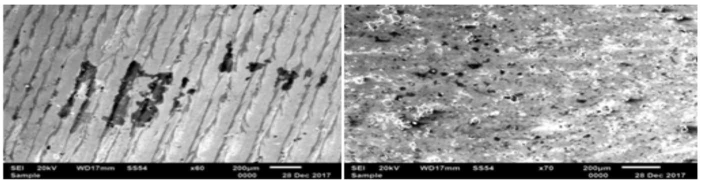

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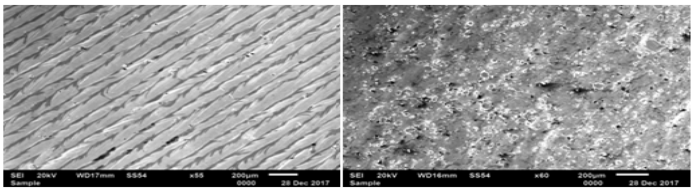

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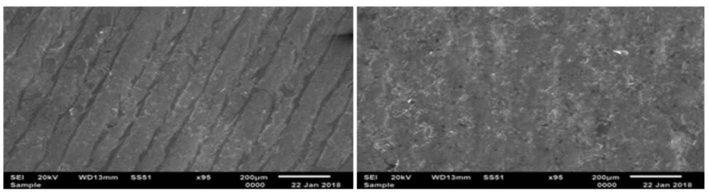
Figure 4: SEM Images Showing Topography of Top and Side Surfaces of as Fabricated Specimens Using Three Different Laser Energy Densities: a) 37.33 J/mm³ b) 61.18 J/mm³ c) 63.72 J/mm³

The higher laser density promotes a stable melt pool with favorable surface tension and wetting characteristics due to an increase in the molten materials temperature resulting in smooth scan tracks free of balling. The microstructure of heat treated Maraging steel specimens at different energy densities are shown in Fig 5. It is observed that fine microstructure, less porosity, and smooth surface are possible with the heat- treated specimens compared to as-fabricated specimens.



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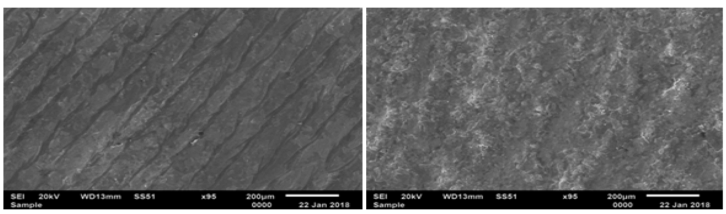

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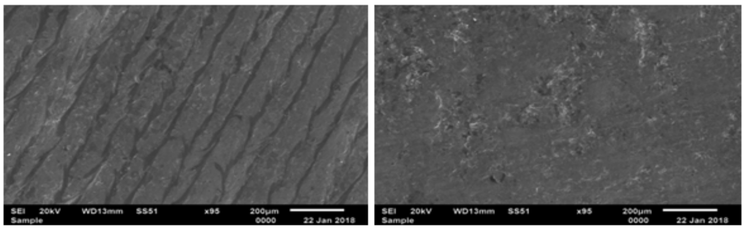

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Figure 5: SEM Images Showing Topography of Top and Side Surfaces of Specimens After Heat Treatment Using Three Different Laser Energy Densities: a) 37.33 J/mm³ b) 61.18 J/mm³ c) 63.72 J/mm³

SURFACE ROUGHNESS

The surface roughness plays as an important role in the accuracy of parts fabricated by DMLS process. Therefore, to characterize and evaluate the surface conditions is of great importance. The lower surface roughness certified the high accuracy of the forming process. The upper and side surfaces of the as fabricated specimens are analyzed in this study. The surface roughness of all samples were measured with Mitutoyo SJ-301surface roughness tester and the values are shown in the Table 3. For example, the surface roughness of the side surface were found to be 7.31 µm for the specimen 15. The surface roughness can be reduced by applying sand blasting operation. Sand blasting is the operation of impacting a stream of abrasive material against a surface under high pressure to get a smooth surface. Sand blasting with steel shots and glass beads retards the fatigue failures by inducing compressive stresses on the metal surface and makes it possible to significantly reduce the surface roughness. The surface roughness are finally reduced from 7.31 µm to 4.57 µm by applying a sand blasting operation at a pressure of 0.8 MPa.

CONCLUSIONS

In the present work High strength maraging steel parts is fabricated by direct metal laser sintering (DMLS) technique. The best Process parameters for direct metal laser sintering (DMLS) of Maraging steel parts are determined using Taguchi design of experiments.

- The observed best process parameters are laser power: 260W, laser scan speed: 850 mm/sec and Hatch spacing: 0.12 mm. The maximum hardness, minimum surface roughness and fine microstructure can be observed at the optimum process parameters.
- The hardness of the as-fabricated Maraging steel parts at the best process parameters are 37.83 HRC. The hardness was improved by applying heat treatment for 6 hours at 490°C. After heat treatment, the hardness was increased from 37.83 HRC to 55.33 HRC due to precipitated-phase strengthening.
- The porosity can be observed in the microstructure at the low energy density. An increase of laser density of 37.33 J/mm³ to 63.72 J/mm³ resulted in less porosity, high hardness, merging of scan tracks and an overall smoothing of a surface. The porosity cannot be observed in the microstructure after heat treatment.
- The minimum surface roughness can be observed at the best process parameters. The surface roughness of the as-fabricated specimen 15 was reduced from 7.31 µm to 4.57 µm by sandblasting operation.

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